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THE SEASONAL VARIATION OF THE STRENGTH OF THE SOUTHERN CIRCUMPOLAR VORTEX

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ABSTRACT

The annual march of the strength of the southern circumpolar vortex is shown to be composed of a simple annual variation (with the maximum occurring in late winter) which dominates in the stratosphere, and a semiannual variation with the maximum at the equinoxes, which is the dominating part in the troposphere. This behavior of the circumpolar vortex is considered to be the consequence of the seasonal variation of radiation conditions and of the different efficiency of meridional turbulent exchange in the troposphere and stratosphere. It is suggested that the semiannual variation of the tropospheric vortex is an essential feature of a planetary circulation. The annual march of pressure with opposite phase values at polar and middle latitudes, can be understood as a consequence of the formation and decay of the great circumpolar vortex.

1. INTRODUCTION

Some aerological data of the Southern Hemisphere and particularly those from the South Pole (Amundsen-Scott Station) obtained during the IGY and its extension through 1959, make it possible for the first time to arrive at an estimate of the seasonal variation in the strength of the southern circumpolar vortex (in the following abbreviated: SCPV) and suggest explanations of the variations.

As a measure of the "strength" of the SCPV consider the geopotential height differences, along isobaric surfaces, between the mean values of three longitudinally almost evenly spaced stations at about 50° S. (Invercargill, Marion Island, and Port Stanley), and the values at the South Pole station. This measure seems to be the best at hand as long as reliable and complete upper-air charts for the Southern Hemisphere are not available. The mean monthly topographies of the isobaric surfaces over Antarctica published in two preliminary IGY Reports (Alvarez and Rastorguev [2]; Alt, Astapenko, and Ropar [1]) do not extend far enough toward the middle latitudes to give adequate measures; moreover, they cover only a part of the period which can now be considered. The South Pole station has been taken as representative of the inner part of the SCPV, in spite of the fact that in several months the center of the vortex cannot be found exactly over the Pole. This does not essentially affect the conclusions to be reached, as the mean pressure gradients (or gradients of height of isobaric surfaces) between 90° S. and the center of the vortex remain always small in comparison to the gradients between the inner polar zone and the middle latitudes.

2. RESULTS

Figure 1 shows the annual march of the height differences for 5 levels from 700 to 100 mb.; the monthly values of a period of 3 years, April 1957 to March 1960, have been used. Table 1 and figure 2 give corresponding values of the amplitude and phase of their first and second harmonic components, and the sum of the amplitudes of the higher harmonics. As the data for 100 mb. were not available for Marion Island, the analysis for the 200-mb. level has been carried out with and without that station,

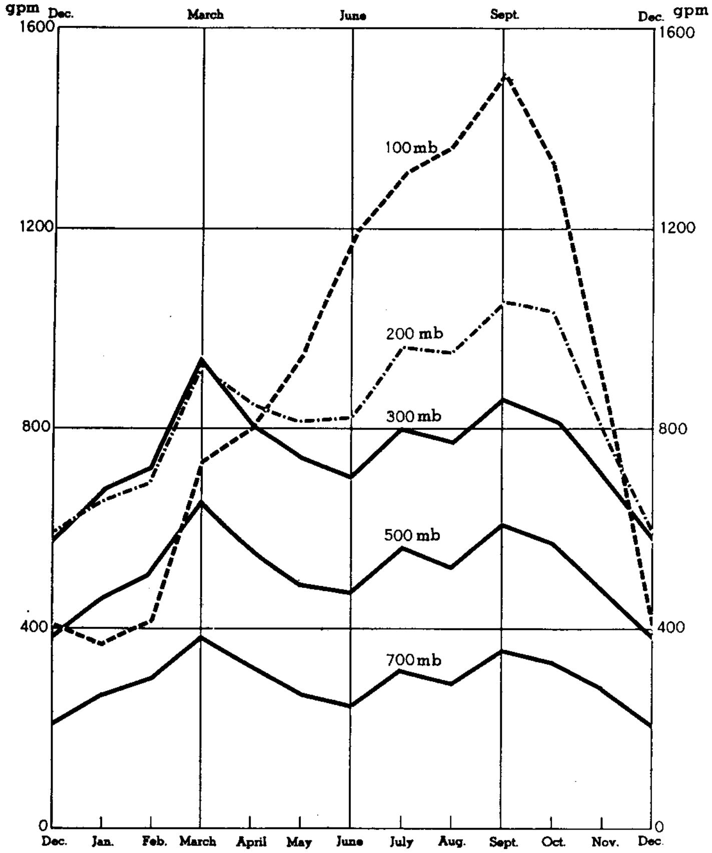

FIGURE 1.—The annual march of the height differences $\overline{H}$ (Invercargill plus Marion plus Port Stanley) $-H$(S. Pole) for 700, 500, 300 and 200 mb., and $\overline{H}$ (Invercargill plus Port Stanley) $-H$(S. Pole) for 100 mb. The location of the three subpolar stations is marked by solid circles in figure 4.

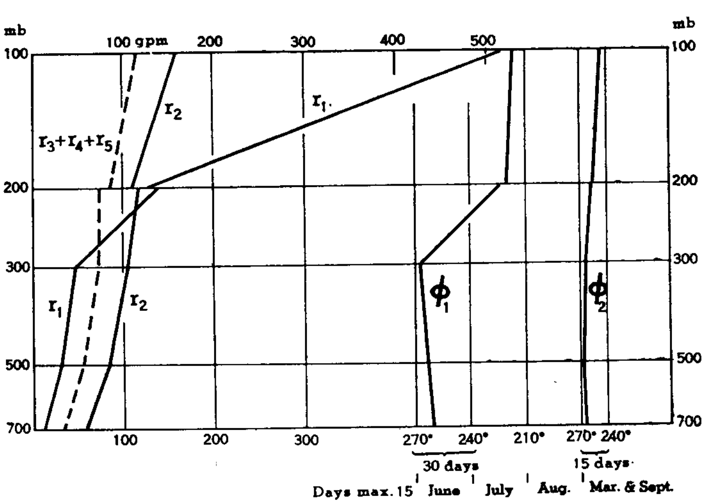

FIGURE 2.—Amplitudes and phases (days max.) of the first and second harmonic component of the annual march of $\overline{H}$ (Invercargill plus Marion plus Port Stanley) $-H$ (Pole), April 1957 to March 1960.

TABLE 1.—*Harmonic analysis of the annual march of the strength of the Southern Polar Vortex: Amplitude (r, in gpm.) and phase (φ) of the first and second harmonic, and sum of the residuals. April 1957 to March 1960.*

(*a*) $\overline{H}$ *(Invercargill, Marion, Port Stanley)* $-H$ *(Pole)*
(*b*) $\overline{H}$ *(Invercargill, Port Stanley)* $-H$ *(Pole)*
(*c*) $\overline{\Delta H}$ *(Invercargill, Marion, Port Stanley; 300–700 mb.)* $-\Delta H$ *(Pole; 300–700 mb.)*

Level (mb.)	Mean	r_1	ϕ_1	Day max.	r_2	ϕ_2	Days max.	$r_3+r_4+r_5$
(a) 700	297	10	260°	25.VI	58	263°	19.III+IX	33
500	523	30	263	22.VI	83	266	17	56
300	760	47	267	18.VI	105	262	20	73
200	841	139	223	2.VIII	119	257	22	75
(b) 200	815	128	219	6.VIII	110	256	22	87
100	937	518	216	9.VIII	160	244	28	117
(c) 300–700	463	39	267	18.VI	48	257	22	40

in order to show that there is no significant difference if Marion Island is included or not. The values in section (c) of table 1 refer to the meridional differences of the thickness of the 700- to 300-mb. layer which are equivalent to the mean meridional tropospheric (virtual) temperature gradient between 50° and 90° S.; for the layer considered, a variation in thickness of 25 gpm. corresponds to a variation of mean virtual temperature of 1° C.

The essential result is that the semiannual component is dominant in the troposphere, with the maxima appearing in the equinoctial months, (that is when the mean meridional temperature gradient is greatest), *and the simple annual component is dominant in the stratosphere.* (For a significance test of the semiannual periodicity, it is better to realize a harmonic analysis of the original series of 36 terms and to apply the method described by Brooks and Carruthers [3], (par. 18, 2), comparing the largest of the 18 possible harmonic components (that is, here the semiannual) with the "expectation"-value on the zero-hypothesis. This was done for the 300-mb. height differences ($\sigma=115$ gpm.) and for the 300–700-mb. thickness differences ($\sigma=57$ gpm.). It results that the amplitude of the semiannual harmonic component of both series exceeds the expectation calculated at the 1 percent level.) As a matter of fact, much more evidence as to the first part of the above italicized statement has been published in recent years (Schwerdtfeger and Prohaska [18, 19], Loewe [11]) and is implicit in other publications (Mintz and Munk [13], Hoffmeyr [7], Schumacher [17]), but for the present discussion it may be sufficient to refer to figures 1 and 2 and table 1. There may be no doubt at all about the second part of the above statement.

3. POSSIBLE EXPLANATION

The possible cause of this behavior of the SCPV can be tentatively assessed from the following considerations: *In the troposphere,* the meridional exchange ("Grossaustausch") between middle and polar latitudes is very strong; the small annual range of temperature, about the same at middle latitudes and polar zone of the Southern

Hemisphere, and especially the peculiar flat temperature curve of Antarctic stations during winter, is mainly due to the vigorous transport of subpolar air masses southward and the corresponding movement of polar air masses northward. The importance of this macro-turbulent process, which is mainly a consequence of the meridional temperature gradient, was recently stressed by Wexler [22, 23]. This meridional temperature gradient shows a characteristic annual march which, as will be discussed later, appears to be related to the seasonal variation of the radiative parts of the heat budget of different latitudinal belts, tending to produce larger mean temperature (or thickness) contrasts between middle and polar latitudes during the equinoctial months than around the solstices. There is a pronounced semiannual variation of the differences of daily totals of incoming radiation between middle (or subpolar) and polar latitudes, as is shown by means of the theoretical values (Milankovitch [12]) in figure 3. Of course, a semiannual variation in the heat budget of different latitudinal belts can be attributed to the effects of incoming solar radiation *only if* the other radiative terms determining the heat budget of the tropospheric air masses, particularly albedo and water vapor content, do *not* themselves show a pronounced *semi*-annual variation. This happens to be so, as far as can be deduced from the scarce observations up to now available; besides, it may be important to mention that in the annual march of the meridional differences of *surface* temperatures, the amplitude of the first harmonic exceeds by far that of the second harmonic.

In order to examine whether the meridional differences of those fractions of extraterrestrial radiation which are absorbed in the troposphere are of the right order of magnitude to be taken as a possible cause of the observed meridional temperature differences, the following assumptions are made: that the layer between 300 and 700 mb. absorbs about (a) 15 percent of the extraterrestrial radiation at 50° S., and 10 percent at 80° S., and (b) 20 percent and 15 percent, respectively (these are only estimates, but are in reasonable agreement with Fritz [4], Liljequist [10] and Hanson [6]). Table 2 gives the differences of the amounts of absorbed radiation in ly./month between latitudes 50° and 80° S.

The essential result is that the amplitude of the second harmonic of the annual march of the "differential heating" exceeds that of the first harmonic, and that its value

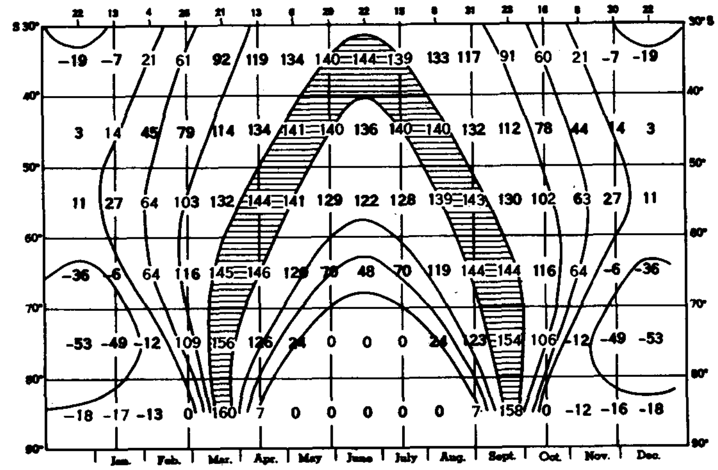

FIGURE 3.—Annual variation of 10° latitude differences of daily totals of incoming radiation between 30° and 90° S. The values are derived from table 1 of the work of Milankovitch [12], with $I=2$ ly./min.

(r_2) is several times greater than that which would be needed, in the hypothetical case of absence of macro-turbulent meridional exchange, to account for the observed value of r_2 in the annual march of the meridional thickness differences (table 1, section c). Therefore, it is strongly suggested that the semiannual variation of the meridional differences of absorbed radiation can bring about the seasonal change of the difference between the mean temperatures (or thicknesses) of middle and polar latitudes, the maxima occurring in the equinoctial months.

In the stratosphere, the conditions are different. The density of the air and the lapse rate being small (for more detailed reasoning see Rubin [15], Wexler [22, 23], and Palmer [14]) the compensating macro-turbulent meridional exchange of air, and therewith of heat, can not be sufficiently efficient. Even if the difference between incoming solar radiation at middle and polar latitudes is greater in March and September than in May through August, the dominating feature is that the cooling of the polar stratosphere continues through midwinter. Therefore, the SCPV in the stratosphere forms again when the incoming solar radiation at the highest latitudes diminishes noticeably and the differential heating begins to favor the middle latitudes, and remains until the springtime heating of the polar stratosphere becomes stronger than

TABLE 2.—*Meridional differences (50°–80° S.) of estimated values of radiation absorbed in the 300–700-mb. layer, ly./month. (a) and (b): Different absorption conditions assumed, as specified in the text.*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
(a)	1510	1960	2190	1790	1110	780	940	1490	2010	2090	1560	1430 ly./mo.
(b)	1490	2250	2820	2360	1480	1060	1220	1980	2680	2570	1750	1290

Harmonic analysis:

(a) $r_1=320$ ly./mo.; $r_2=530$ ly./mo.; $\phi_1=79°$; $\phi_2=260° \approx$ max. at Mar. and Sept. 20
(b) $r_1=160$ ly./mo.; $r_2=810$ ly./mo.; $\phi_1=79°$; $\phi_2=258° \approx$ max. at Mar. and Sept. 21

that of the surrounding latitudinal belt. It can be estimated that that occurs during the month of October, more likely in the second half of it, because the daily totals of incoming radiation are slightly less at the Pole until the second half of November but, on the other hand, the ozone concentration is higher in the polar zone than in middle latitudes. From October to December, when the annual and the semiannual variation of the SCPV are running in phase, the vortex breaks down in the upper layers and goes towards its minimum strength in the troposphere.

Thus, combining the considerations for troposphere and stratosphere, it appears that the simple annual variation in the strength of the SCPV should increase with height much more than the semiannual variation, as the efficiency of meridional exchange diminishes with increasing height and the summertime heating, because of the effects of ozone, is restricted to the upper levels. That is essentially what the data in table 1 confirm. The relatively small increase with height of the second harmonic component in the stratosphere can be attributed to the lesser effects of the meridional differences in available energy on the difference between the heat budgets of middle and polar latitudes, and partially, also, to the asymmetry in time and increasing annual range of the yearly temperature curve of the polar stratosphere with height.

For completeness, the above qualitative statements should be supported by numerical estimates of the decisive terms. This is, of course, beyond the aim of the present note.

4. CONSEQUENCES

If the behavior of the SCPV is understood as the combined result mainly of radiation processes and macro-turbulent meridional exchange, some important consequences can be tentatively outlined:

(1) For the formation of the *semi*-annual variation of the SCPV, which is dominant in the troposphere and still quite noticeable in the lower stratosphere, the existence of the Antarctic continent is not an essential point (and, of course, neither is that of the other land masses of the Southern Hemisphere). Generally speaking, and referring only to the second harmonic of the annual march, the same should happen if the Antarctic did not exist. *Therefore, the semiannual variation in the strength of the SCPV may be considered as an essential feature of a planetary circulation.* As far as the author knows, this point was never mentioned in any work on the general atmospheric circulation, but it could have some importance for theoretical and perhaps also for experimental studies.*

(2) The slow buildup and fast breakdown of the SCPV, with the semiannual variation the dominant characteristic in the troposphere (that is, in the layer of the main part of the mass of the atmosphere), is nicely reflected in the mean annual variation of pressure at the surface. In 1955 and 1956, Schwerdtfeger and Prohaska [18, 19] published an analysis of the annual march of pressure for the world, trying to include for the first time the whole Southern Hemisphere. It was shown that there exists a very pronounced semiannual oscillation over the extratropical southern latitudes, with opposite phase values in polar (maxima at the solstices) and middle (maxima at the equinoxes) latitudes. This result, based on relatively short series of data south of 50° S., was supported by the data from an entirely independent study of Gordon [5], who considered the monthly change of mass of different latitudinal belts of the atmosphere between the *North* pole and 50° *S*. The corresponding values south of 50° S. have been computed by Schwerdtfeger ([21] table 2). The concept of a well marked semiannual pressure oscillation in polar regions is now also confirmed by the somewhat longer series of observations available at the end of the IGY. Schwerdtfeger and Prohaska [18, 19] suggested that the semiannual component in the yearly march of pressure over the extratropical part of the Southern Hemisphere is directly related to the corresponding variation in the strength of the circumpolar westerlies, and some evidence for this was brought forward by the authors and by Loewe [11]. It can now be said more explicitly that the annual march of surface pressure over polar and middle southern latitudes should be considered the consequence (the "demonstration at the surface") of the annual march of the strength of the SCPV. It does not seem necessary to reproduce here the already published results of the harmonic analysis of the Southern Hemisphere pressure field. However, it is interesting to point to the mean change of pressure at the surface, related to the "breakdown" of the SCPV (from October to December, fig. 4).

(3) The semiannual variation of the mass of the polar atmosphere is of such an order of magnitude (the amplitude of the second harmonic amounts to about 3 per mille of the mass south of 60° S., the maxima occurring at the solstices) that its effect on the angular velocity of the earth, i.e., the length of day, must be noticeable. It appears that the calculations of Mintz and Munk [13] can thus be refined.*

(4) Finally, it should be remarked that the old notion of classic climatology, not objected to until 1955 (Schwerdtfeger and Prohaska [18]), that the semiannual oscillation of surface pressure may have its main origin in the equatorial zone, cannot be maintained in the light of the results from the Southern Hemisphere.

Additional remark, referring to the occurrence of a semiannual variation in the strength of the tropospheric circumpolar westerlies at high *northern* latitudes: In the case of the Northern Hemisphere, it can not be expected that the zones of equal heat budget be latitudinal belts and that the meridional temperature gradients at higher

*Scherhag's [16], contention, that "all essential features of a planetary circulation can be seen from the mean annual topography of the 1000 mb. surface [sic!] of the southern hemisphere," can hardly be accepted.

*This problem will be considered in a separate paper.

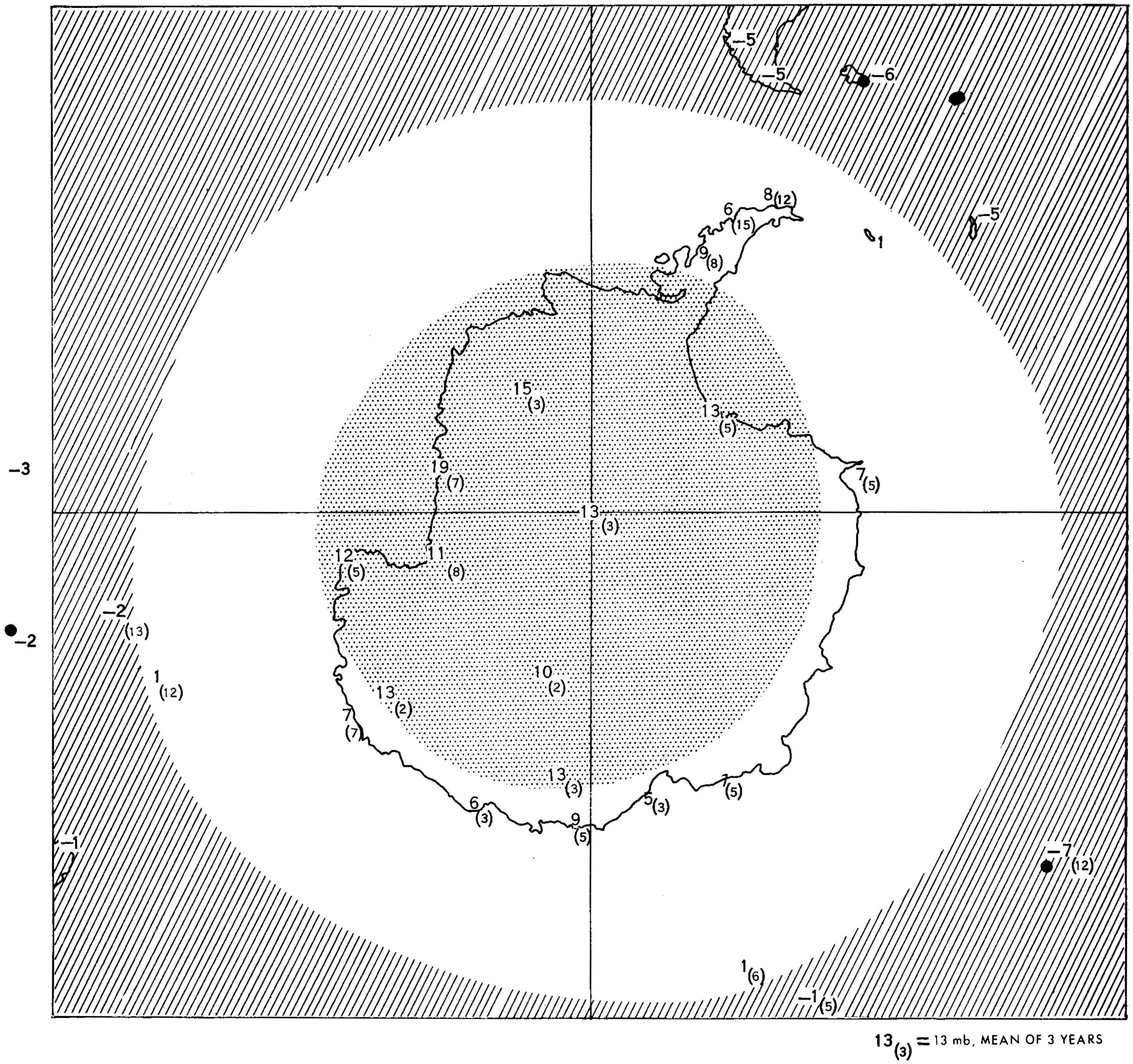

FIGURE 4.—Mean pressure change (mb.) from October to December, Southern Hemisphere south of 40° S. Hatching shows zone of negative values; stippling, zone of values > 10 mb. For all stations with a record less than 20 years, the number of years used is put in parenthesis.

TABLE 3.—*Latidudinal means: (a) u-component of the geostrophic wind at 300 mb., average of 65°, 70°, and 75° N., 1950–57, computed from Lahey, Bryson, et al. [9]; (b) 500–1000-mb. thickness differences, 60°–80° N., (20 gpm. ≈ 1° C.), 1900–39, computed from Jacobs [8].*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
(a)	6.8	6.6	8.0	7.6	6.2	6.4	7.0	7.6	8.8	9.0	7.9	7.1/ m./sec.
(b)	124	139	196	200	168	143	146	155	169	184	150	135 gpm.

Harmonic analysis

(a) r_1=0.7 m./sec., max. at October 15; r_2=0.9 m./sec., max. at Mar. and Sept. 28.
(b) r_1=11 gpm., max. at May 18; r_2=30 gpm., max. at Apr. and Oct. 6.

latitudes show the equinoctial maxima at all longitudes. Nevertheless, even there the effect of stronger meridional temperature differences around the equinoxes is evident in the mean values (table 3). Considering the pronounced regional contrasts in surface conditions of this latitudinal belt, the fact that $r_2 > r_1$ may be interpreted as supporting the notion that the semiannual variation of the meridional differences of absorbed short-wave radiation is at least one of the causes of the semiannual variation of the strength of the circumpolar vortices.

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